LIFETIMES OF 2^+ AND 4^+ STATES OF Dy-160

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ABSTRACT. The half-lives of the first and second excited states of Dy-160 are measured by the delayed coincidence method. For this measurement, a time-to-amplitude converter is assembled. With NaI(Tl) crystals on both the photomultipliers, a resolving time of 2.4ns with an intrinsic time resolution of 0.27ns is achieved down to an energy of 200Kev The life-times of 2^+ and 4^+ levels of Dy-160 are obtained at T $(2^+)=1.94\pm0.097$ns and $T_{\frac{1}{2}}(4^+)=(11.25\pm1.13)\times10^{-11}$ sec. These values confirm those obtained by Li and Schwarzchild. The results of the present investigation are discussed and found to confirm the predictions of the unified nuclear model.

INTRODUCTION

Recently Li and Schwarzchild (1963) have measured the lifetimes of 2^+ and 4^+ states in four different isotopes (including Dy-160) which belong to the strongly deformed region. Their results have been found to be in agreement with the predictions of the unified nuclear model (Bohr, 1952). The results obtained by some of the workers, however, show deviations with the predictions of the unified model. These deviations may be ascribed to those arising out of the measured lifetime values. The recent developlent of the time-to-amplitude converters has enabled the attainment of a better accuracy in the measurement of the lifetimes. These converters enable the attainment of the time spectral data employing a multichannel analyser. This use naturally reduces the duration of the experiment thereby rendering the minimization of the various systematic errors. The time-to-amplitude convertor which is already mentioned, is so modified as to match the characteristics of the NaI(Tl) crystals employed in the present investigations inorder to measure the lifetimes of the 2^+ and 4^+ levels of Dy-160.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement in the present investigations involve two scintilation heads arranged in triple coincidence. The scintillator-photomultiplier assembly consists of a NaI(Tl) crystal 4.45 cm in diameter and 2.54 cm in height. Whenever the investigation involves the observation of beta-decay, an anthracene scintillator (4.45 cm in dimater and 0.32 cm in thickness) is employed in the beta-channel. The block diagram of the arrangement is shown in Fig. 1. The pulses

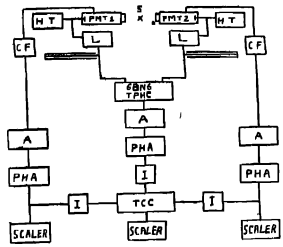

Fig 1. Block diagram of the experimental set-up.
S—Source; H.T.—High Tension; PMT—Photomultiplier, L—Limitor; C.F.—Cathode follower; TPHC—Time-to-pulse height converter; A—Amplifier; PHA—Pulse height analysier; I—Inverter; T.C.C.—Triple coincidence circuit;

from the anodes of the photomultipliers are transmitted to the limiters the outputs of which are so clipped as to obtain pulses of 80ns duration, which in turn are fed to the 6BN6 time-to-amplitude converter of the Green and Bell (1958) type. The output of the converter is connected to the triple coincidence circuit via an amplifier followed by an analyser. It may be pointed out that the pulses from the eighth dynodes of both the photomultipliers are amplified, energy selected and then transmitted to the triple coincidence unit, the output pulses of which are recorded by means of a decade scaler.

The decay time of the NaI(T1) crystal is approximately 300ns. Hence only a minute part of its pulse is applied to the converter inorder to achieve a good time resolution by operating the photomultipliers at voltages upto 2400V. The amplitude of the resulting pulse is of the order of 150V especially in the case of a gamma component with an energy of 511Kev as given out by Na^{22} annihilation quanta. The arrangment of the fast pulse part of the converter is shown in Fig. 2

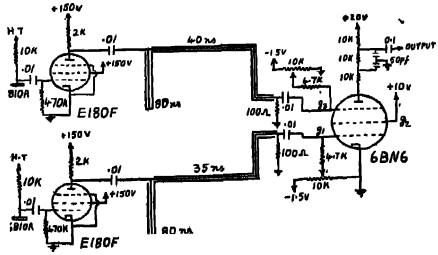

Fig. 2. Fast coincidence arrangement.

in which the converter part is identical with the original one (Green and Bell 1958) In the present arrangement the limiters are of Special Quality Philips E180F tubes operated at a plate potential of 150V. The limiter has a cut-off value less than 2 volts at the operating conditions. The screen potential is so adjusted as to obtain a plate current of 22mA. The clipper in the fast channel is a cable of the type AS48M with an impedance of 100 ohms, a capacitance of 12pf/ft, and a delay of 1.2ns/ft. The distortions which may occur in the rising and falling portions of the shaped pulses are eliminated by employing a fixed delay of 40ns in both the channels of the converter. The valve 6BN6 is operated at potentials of 20V and 10V to the plate and screen respectively. With these operating conditions, the pulses with one volt amplitude can saturate the plate current, as the grids g_1 and g_3, as shown in Fig 1, are held at negative potentials of 0.7 and 1.0 volt respectively. Since the plate current of the limiter is adjusted at 22mA, and the effective impedance of the clipping stub is 50 ohms (obtained with 100 ohm terminating resistance in parallel), the pulses have a height of 1.1V. It may be mentioned that at these operating conditions of the 6BN6, there is an inherent delay of 5ns arising out of the transit time of electrons from grid g_1 to g_3 Complete overlap of the pulses at g_3 is effected by inserting 35ns cable in g_1 and 40ns in g_3. When two simultaneous pulses arrive at the two grids of the 6BN6, a current flows during the time the pulses overlap. Since the plate pulse is integrated, the charge accumulated on the plate is proportional to the overlap time of the pulses so that the amplitude of the pulse obtained from the converter is proportional to the delay between the two pulses.

The introduction of a fixed delay of 40ns in both the channels affords a simultaneous comparison with the prompt coincidence curve. The slopes on the two sides of the coincidence curve arise out of the jitter in the time of arrival of the pulses at the grid of the limiter. When the time jitter is symmetrical, the prompt coincidence curve is symmetrical in shape. With a measurable lifetime, the delayed radiations are detected only in one of the counters hence the distortion of the lifetime is imposed on only one side of the coincidence curve. The plot of the delayed coincidence has a slope as expected for a prompt cascade being of the same energies, whereas the other side has the slope corresponding to the lifetime. With the introduction of a delay of 40ns in both the channels the present arrangement has a useful range of 0-40ns. The negative output of the converter is fed to a high gain linear amplifier through a cathode follower. A single channel analyser which follows the amplifier is used to scan the time spectra. The voltage scale of this analyser is calibrated in terms of time by observing the shift in the centroid of the prompt curve for every 5ns decrease of the cable in one of the channels. The amplifier in the fast channel is kept in one of the two adjusted gain positions corresponding to the calibration values of 0.909ns/volt and 0.425ns/volt for the measurements in the nanosecond and sub-nanosecond regions. The prompt curve has resolving time of 2.4ns with slopes corresponding to half-lives of 0.27ns

for energies down to 200Kev. For energies below 100Kev, the resolution is nearly 3ns. With anthracene-photomultiplier assembly, the operating voltage is only 2000V. This reduction from 2400-2000V enables the limiting of the anode pulse to 6-8% of the amplitude thereby obtaining the best possible resolution, the resolving time in this case being 2.1ns with slopes of 0.26ns. To test the accuracy of the lifetimes of the excited levels in the isotopes under investigation, the lifetimes of the level with an energy of 81Kev of Cs-133 and the level with an energy of 279 Kev of Tl-203 are observed and found to have the values of the half-lives as 6.09 ± 0.3ns and $(2.89 \pm 0.14) \times 10^{-10}$sec respectively. These values are quite in agreement with the results of the previous workers. In other words, the oft measured values of the lifetimes of these isotopes taken as standards are employed for testing the verity of the lifetimes measured with the present equipment

Determination of lifetime of the 2⁺ state of Dy-160.

The decay scheme of Tb-160 is quite complicated as can be seen from the level diagram (Ewan *et al.* 1961) given in Fig. 3. The figure indicates most of the intense

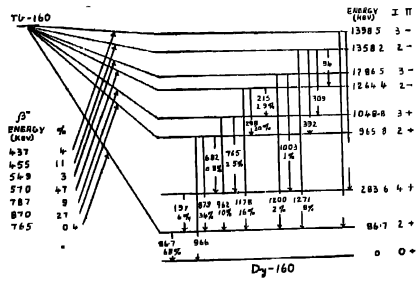

Fig. 3. Decay scheme of Tb-160 (Ewan et al.)

transitions along with the percentage of intensities. It can be seen that there are seven beta groups and nearly twenty gamma transitions, hence the spectroscopic measurements are difficult. It may be pointed out that the 2⁺ and 4⁺ states have been identified as members of the K = 0 rotational band, whereas the higher 2⁺ and 3⁺ excited states have been identified as those of the K = 2 band resulting from electric quadrupole vibrations. The values of the half-life for the 2⁺ level obtained by different authors are tabulated as given in Table I.

From this table I it is interesting to find that the values of (1), (4) and (5) are in good agreement within the limits of experimental, error; of which those in (4) and (5) are of relatively high precision. On the other hand, the results from (2), (3) and (6) are at variance with one another. The recently measured value[9] 2.059 which is given within a precision of ± 0.016ns, is at variance with all the

TABLE I

	Author and year		Half-life (ns)	Reference
1.	F. K. McGowan	(1955)	1.8 ±0.2	5
2.	Berlovich et al.	(1962)	1.6 ±0.1	6
3.	Richter and Wiegandt	(1962)	2.25±0.06	7
4.	Fossan and Herskind	(1963)	1.92±0.05	8
5	Li and Schwarzchild	(1963)	1.99±0.05	1
6.	De Boer et.al.	(1963)	2 059±0.016	9
7.	Elbek et.al.	(1960)	2.247±0 14	10

already mentioned values. Under these circumstances it is considered necessary to reinvestigate the lifetime of the 2^+ level using the equipment developed for the purpose. To study the decay scheme, Terbium-160 is obtained in liquid form as Terbium chloride with an intensity of 5.2mC. A small quantity of this liquid is taken in a perspex tube and is mounted on the source mount situated symmetrically between the two scintillation heads. Then the singles spectrum of Tb-160 is recorded. The 87Kev transition being highly populated (nearly 68%), is very intense. Hence a gamma-gamma coincidence study is very desirable for this intense case. The gamma-gamma coincidence involves the record of counts when the detecting units are arranged at right angles to one another and the crystals are covered with 1 mm of lead to cut-off the characteristic X-radiation. The 87Kev gamma component is chosen for observation by one scintillation head, the other being biased at an energy of 600Kev so that those gamma photons feeding the 87Kev level are collected for coincidence. The resulting coincidence spectrum is recorded as shown in Fig. 4. Each experiment is repeated thrice, the total number of separate experiments being four. The resulting average half-life value

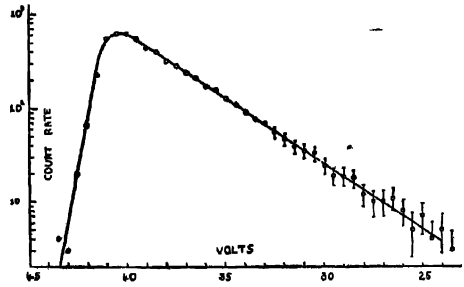

Fig. 4. Lifetime measurement of the 2+level.

obtained by least square fit analysis is $T_{\frac{1}{2}} = 1.94 \pm 0.035$ns. This error together with the errors arising out of the instrument, calibration, and those arising out of the measurement of the length of the cables comes to a total value of 5% so that the corrected half-life may be written as $T_{\frac{1}{2}}(2^+) = 1.94 \pm 0.097$ns which is not in agreement with some of the listed values [6, 7, 9].

Determination of the lifetime of the 4+ level of Dy-160

The 283Kev excited level of Dy-160 deexcites to the 87Kev level by a transition with an energy of 197Kev. The 4^+ level is of meagre population being only 5% in the decay of Tb-160. This transition also involves to total conversion of nearly 25% The transitions between the 1264 and 966Kev levels as well as between 1264 and 1049Kev levels give rise to conversion electrons of intensity comparable to that of the above transition If the 765.2Kev transition be selected in one of the channels and the 215-197 Kev transitions in the other, the lifetime of the 1049 Kev level may influence the value of the lifetime of the 4^+ level. The upper levels have energies of large value and mostly are decaying by E2 transitions. Hence the single particle estimates predict very short lifetimes (of the order of 10^{-12} sec) for these levels. Therefore, they are not expected to influence the lifetime of the 4^+ level. The results of the measurements on the lifetime of the 4^+ level carried out by previous workers are tabulated as given in Table II

TABLE II

	Author	Year	Half-life (10^{-11} sec)	Method	Reference
1.	Burde and Rakavy	1961	7.56 ± 0.76	Self comparison	11
2.	Berlovich et.al.	1962	7.10 ± 0.90	Centroid shift	6
3.	Li and Schwarzchild	1963	10.7 ± 0.50	Slope	1

The first two mentioned values in Table I, though are in fair agreement, differ very much from the last one. The first result in the table is obtained by employing two double lens magnetic spectrometers in coincidence along with a time-to-amplitude converter. The second in the list employed a centroid shift method for measuring the lifetime in the decay of Ho-160 in which the coincidences are measured between the upper gamma components and the conversion electrons. The last mentioned data is obtained by employing a precision time-to-amplitude converter having a slope of 4×10^{-11} sec along with a three crystal spectrometer.

In the present investigations an attempt has been made to measure the lifetime of the same level but with the equipment developed for the purpose. In a certain sense this unit is very sensitive with high efficiency and with a good resolution. In experiments which involve beta-electron or beta-gamma coincidences

the number of prompt coincidences may be very large because of the interference of the upper levels. The scintillation heads as already mentioned, subtend an angle of 90° and the crystals are covered with 1 mm of lead to arret X-photonss. One of the slow channels is set to accept the peak with an energy range of 197-215Kev, the other being biased at about 600Kev. The number of prompt coincidences given out by the 215-765Kev cascade is nearly 20% and as the 1049Kev level lifetime is expected to be very short, the uncertainty in the lifetime is expected to be less than the assigned errors The gain of the amplifier in the fast channel is set at the position of the higher sensitivity whereas the converter circuit is kept in the 60ns overlapping condition obtained by replacing the cable in the g_1 channel with a cable of length 20ns After these preliminary arrangements the time spectrum is scanned obtaining a curve, the inverse of which is taken by the interchange of the selection of the gamma components. The two sets of data thus obtained are plotted, after eliminating the errors arising out of chance coincidences, on a semi-logarithmic scale as given in Fig 5. A similar procedure is adopted using

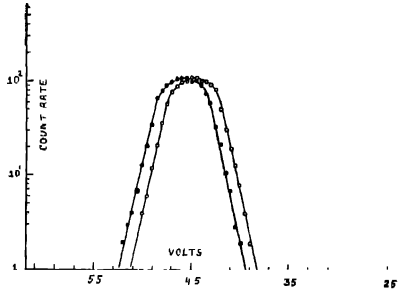

Fig. 5. Lifetime measurement of the 4+ level.

a Co-60 source, with the same energy selections, in order to eliminate the errors due to time-independent and energy-dependent shifts. The resulting spectra thus obtained are shown in Fig. 6. The centroid shifts (2τ) are determined by numerical integration and are converted to time by comparison with the calibration plot used as standard. The shift for Tb-160 thus determined corresponds to a half-life of 16×10^{-11} sec whereas that for Co-60 corresponds to 4×10^{-11}sec giving the value of the half-life of the 4^+ level as 12×10^{-11}sec. The entire experiment is repeated using a different intensity of the source. The result of this repetition is found to have a value of 10.5×10^{-11}sec. Assuming the possibility of 10% error in these measurements, the average value for $T_{\frac{1}{2}}(4^+)$ is found to be

$$T_{\frac{1}{2}}(4^+) = (11.25\pm1.13)\times10^{-11}\text{sec}.$$

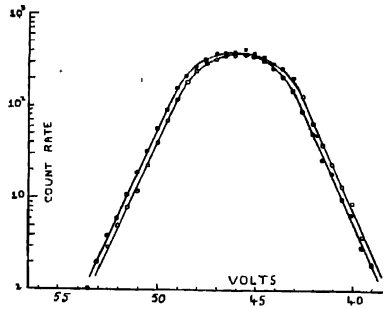

Fig. 6. Experiment with Co-60.

which is indeed in agreement with the latest value listed in the table.

DISCUSSION

It is usual that the experimental transition probabilities are compared with the values computed from the theory of single particle model. To obtain the experimental transition rates, the 197 and 86.7Kev transitions of Dy-160 are considered as having no admixture. It is required that the values of the experimentally determined lifetimes be corrected for internal conversion. The theoretically obtained total internal conversion coefficients[12] are found to be 4.60 and 0.25 for the 86.7 and 197Kev transitions respectively. Thus after the necessary corrections the experimental transition rates $T(E2)_{86\cdot7}$ and $T(E2)_{197}$ are found as

$$T(E2)_{86\cdot7} = 6.392\times10^{7}\ \text{sec}^{-1}$$

$$T(E2)_{11} = 4.939\times10^{9}\ \text{sec}^{-1}$$

The values of the transition rates corresponding to the above are derived from the single particle model and are found to be $3.148\times10^{5}\ \text{sec}^{-1}$ and $1.907\times10^{7}\ \text{sec}^{-1}$ respectively. It can be seen that the experimental values are comparatively much higher by an order of 203 and 259 respectively than the theoretically obtained values. This enhancement is expected in the strongly deformed region for E2 transitions within a rotational band. However, the K-forbidden E2 transitions have retardation factors of the order of 10^{3}.

With a view to see the present experimental transition rates are capable of confirming in a more satisfactory way the predictions of the strong coupling model, the present experimental results for the transition rates are compared with the predictions of the strong coupling model, In this connection it may be

pointed out that the reduced transition probability $B(E2)$ of an $E2$ transition from an initial spin state I_i to the final state I_j in a rotational band K is

$$[B(E2);\ I_i \rightarrow I_f] = \frac{5}{16\pi}\, e^2 Q_0^2 <I_i 2KO \mid I_i 2 I_f K>^2 \qquad \ldots\ (1)$$

where Q_0 is the intrinsic quadrupole moment. Substituting the experimental values in the expression

$$[B(E2)]_{exp} = [1.23 \times 10^{-2} \times E_\gamma^5]^{-1} T(E2) \qquad \ldots\ (2)$$

the $B(E2)_{86\cdot7}$ and $B(E2)_{197}$ are obtained as

$$B(E2)_{86\cdot7} = 1.061(e^2 10^{-48}\ \text{cm}^4)$$

$$B(E2)_{197} = 1.352(<) e^2 10^{-48}\ \text{cm}^4)$$

Again substituting the above values of the $B(E2)$ in the expression (1), the Q_0 values are obtained as

$$Q_0 = 7.302 + 0.18 (10^{-24}\ \text{cm}^2)$$

$$Q_0 = 6.901 \pm 0.35 (10^{-24}\ \text{cm}^2)$$

being those determined from the lifetimes of the first and second excited states respectively. It can be seen that the Q_0 values for both the levels are as should be in agreement within the limits of the experiment. From the value of Q_0 given above the deformation parameter β is derived from

$$Q_0 = \frac{3}{\sqrt{5\pi}}\, ZR^2\beta \qquad \ldots\ (3)$$

as $\beta = 0.3443$.

The value of the intrinsic quadrupole moment Q_0 may further be tested by employing the result derived from the Asymmetric Rotor Model[13]. Using this model the Q_0 is obtained from

$$[B(E2); 2^+ \rightarrow 0^+] = \frac{e^2 Q_0^2}{16\pi}\, \frac{1}{2} \left(1 + \frac{3 - 2\sin^2 3r}{\sqrt{9 - 8\sin^2 3r}}\right) \qquad \ldots\ (4)$$

where r is the (shape) parameter of transverse deformation. In the case of Dy-160, from the energies of the first and second excited states, the r is found to be 11.85° which on substitution in the above expression (4) gives the Q_0 value as $Q_0 = 7.44$ $(10^{-24}\ \text{cm}^2)$ which is in agreement with that obtained from the unified model. Hence it may be concluded that there is not much difference in the results

obtained from unified and asymmetric rotor models in the strongly deformed region.

The expression (1) gives a value of 1.43 to the ratio of the reduced transition probabilities $[B(E2); 4^+ \rightarrow 2^+]/[B(E2); 2^+ \rightarrow 0]$. On the other hnd, the experimental value of the same is obtained as 1.275 ± 0.2. It can be seen that these two values are in a fair agreement. The assigned error 0.2 of the ratio amounts to 16% which naturally as can be seen from the following table is considerably less than those of others.

TABLE III

	Authors	Year	$\left[\frac{B(E2)\ ;\ 4^+ \rightarrow 2^+}{B(E2)\ ;\ 2^+ \rightarrow 0^+}\right]$	Same ratio calculated with $T_{\frac{1}{2}}(87) = 1.94$ns.
1.	Burde and Rakavy	1961	$1\ 650 \pm 0.33$	$1.897 \pm 0\ 33$
2.	Berlovich et.al.	1962	1.680 ± 0.27	2.019 ± 0.27
3.	Li and Schwarzchild	1963	1.400 ± 0.22	1.341 ± 0.22
4.	Present investigation		1.275 ± 0.20	1.275 ± 0.20

From the last column of the table it can be seen that with the value obtained by present investigation for the lifetime of the 2^+ level, the values of the ratio differ considerably from the theoretical value (1.43) in the case of the results of the authors (1) and (2) mentioned in the table. From the data[1] of four even-even nuclei in the strongly deformed region it can be seen that the values obtained for the same ratio are in good agreement with the theory. Hence the present experimental value for the ratio of the reduced transition probabilities within the $K = 0$ band confirm the unified model predictions. It can also be seen that the present lifetimes of the 2^+ and 4^+ levels are accurate within the limits of the experiment.

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